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SHOCK WAVE STUDIES OF SNOW

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Shock-wave studies of snow have been conducted at stress levels of up to 40 MPa. Analysis of embedded gauges and shock-reverberation techniques were used to determine shock pressure-density data for snow with initial densities ranging from 100 kg m^{-3} to 520 kg m^{-3} and temperatures ranging from -2 °C to -23 °C. Shock velocities ranged from about 170 m s^{-1} (for low density snow) to about 280 m s^{-1} (for high density snow). At constant density and impact velocities, but varying temperatures, there was no variation in shock velocity. This indicates that the internal energy and any temperature dependent strength of ice bonds do not measurably affect shock propagation in snow over the temperature and pressure range of our tests. Our results also indicate that snow is a highly rate sensitive material.

1. INTRODUCTION

Understanding the shock compression of snow is of interest for its direct application to such fields as planetary sciences, cold regions and military engineering, and shock isolation. The only existing data obtained with reliable experimental methods are the high pressure data (3.8-35.4 GPa) of Bakanova et al.[1]. We have conducted a test program using embedded stress gauges to obtain pressure density relations for snow at low pressures (up to 40 MPa). Experiments were conducted to examine the effect of initial density (100 kg m^{-3} to 520 kg m^{-3}) and temperature (-2 °C to -23 °C) on shock propagation in snow.

2. EXPERIMENT AND DATA ANALYSIS

A 200 mm diameter gas gun was used to shock load the snow. The snow target assembly consisted of a snow filled copper cylinder capped in front with a buffer plate (consisting of a carbon film stress gauge epoxied between two aluminum plates) and an aluminum back support plate. Stress-time records were measured using 50-ohm carbon-film piezoresistive stress gauges embedded in the snow at nominal distances of 14-mm, 28 mm, and 42-mm from the buffer plate. Thermocouples and cold nitrogen gas circulating through a cooling coil attached to the copper cylinder were used to monitor and control snow temperature. Details of sample preparation methods and instrumentation are given in Brown et al.[2] and Johnson et al.[3].

The unsteady nature of shock wave propagation in the snow, specialized sample preparation methods, and large impedance mismatches between the snow and stress gauges resulted in complex stress histories. We used the PRONTO 2D[4] dynamic finite element program to determine the reasons for distinctive features in the measured stress histories and to determine loading, unloading, and reloading paths for the snow[3, 5].

Data were also analyzed by using a simplified model that treated the shock loading experiment as quasi-steady with changes in pressure and shock velocity caused by unloading from the aluminum buffer. Known equations of state for aluminum were used in calculating partic'e velocities and stresses at the buffer/snow interface.

Figure 1 shows an x-t (distance-time) diagram of our quasi-steady "reverberation analysis". The solid and dashed lines in the figure represent shock and release waves, respectively. The reverberation analysis assumes that the stress transferred through the aluminum buffer into the snow is constant from the instant the flyer plate (A) impacts the buffer plate (B and C) until the release wave from the back of the flyer arrives at the gauge embedded in the aluminum buffer (between B and C). Tensile stresses produced by the release wave cause the buffer to fail at the gauge[3]. Unloading in the snow then occurs by multiple reverberations in the separated buffer plate (C) which remains in contact with the snow.

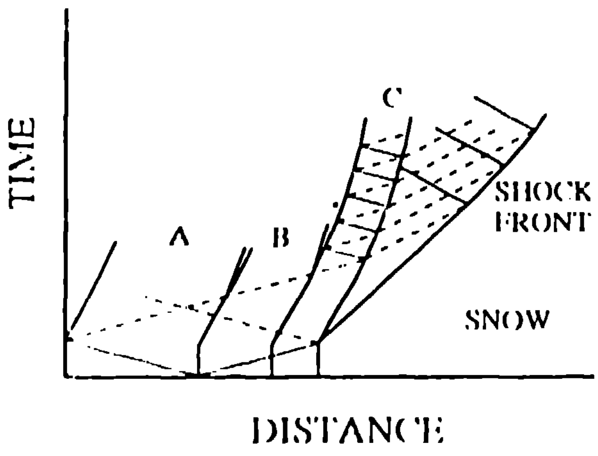

FIGURE 1
x-t diagram for the shock loading experiment on snow. The flyer plate (A) separates from the buffer (B and C) and the buffer plate separates at the B/C interface upon arrival of the flyer release wave.

The measured flyer impact velocity, and the arrival time of the shock wave at stress gauges in the snow were used to determine the particle velocity and estimate pressure at the buffer plate/snow interface. Particle velocities and pressures in the snow were calculated by using conservation of mass and momentum, and equality of pressure and particle velocity at the buffer plate/snow interface and the shock front. Unloading behavior was determined by varying the modulus of the snow behind the shock wave front until calculated arrival times at the stress gauge positions agreed with measured values.

Pressure versus density (P-ρ) results from the reverberation analysis were used in PRONTO 2D to model the experiment; model results were again compared to measured arrival times. Arrival times calculated using the reverberation analysis agreed with those calculated using PRONTO 2D and measured values to within 5% to 20%. This agreement justifies our assumption of quasi-steady wave propagation in the reverberation analysis.

3. RESULTS AND DISCUSSION

Pressure versus density for snow determined from our tests and from quasi-static tests of Abele and Gow[6] are shown in Figure 2. Calculated release moduli are shown in Figure 3. The effects of initial density and strain rate are both apparent from the data.

Shock velocity in the snow versus initial snow temperature, at constant particle velocity and with similar initial density, are given in Figure 4. The lack of any discernable dependence of shock velocity on sample temperature indicates that internal energy variations of snow and any temperature dependent strength of ice bonds do not measurably affect shock propagation in snow over the temperature and pressure range of our tests

The samples used in the shock velocity/ temperature tests had density variations of ± 10 kg m^{-3} due to natural variations in available snow. Our snow samples were also collected at different times and locations. Consequently, aging time for the samples was variable (i.e., the time available for ice bond growth to occur in a sample) and may have produced samples with different ice bond strengths. Insensitivity of our results to small density and ice bond strength variations indicate that the initial strength of ice bonds between snow grains may not significantly affect shock propagation in snow. This differs from Brown's[7] theory of shock wave propagation in snow in which the

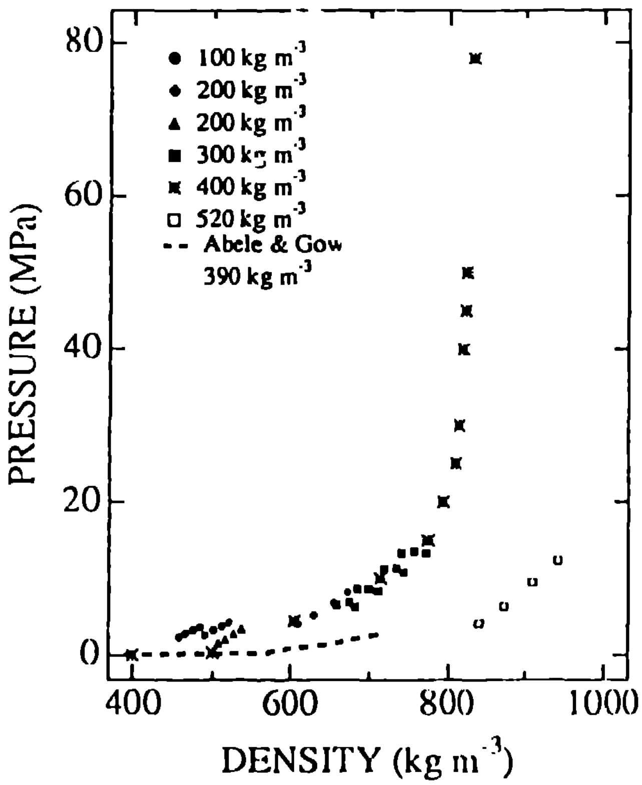

FIGURE 2
Pressure versus density for snow Abele and Gow's data was obtained using quasi-static tests.

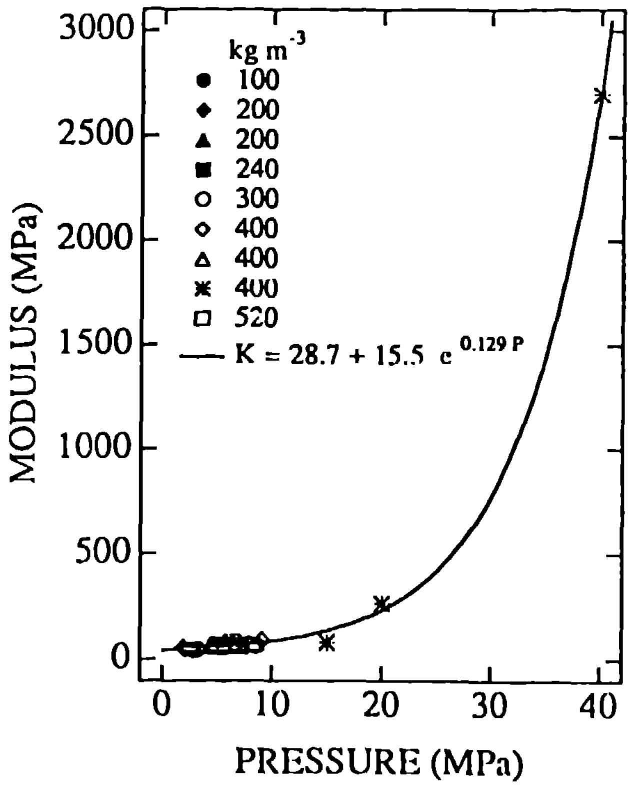

FIGURE 3
Initial release modulus for snow.

initial ice grain bond neck size is thought to control subsequent shock behavior.

Shock compaction of snow may occur in a fashion similar to that suggested by Boade[8] for copper. A shock wave travelling in snow is likely to have sufficient amplitude to immediately overcome the bond strength between grains creating an unconsolidated porous material. The grains are then driven together without being significantly deformed, resulting in a density that is close to the maximum that can be obtained by grain packing. Further compaction produces large plastic deformation of the snow grains causing them to flow together, rapidly reducing the inter-grain void space. Quasi static test results for uniaxial and shear strength versus density in snow exhibit a distinct strain hardening at a density of about 500 kg m^{-3}, which is near the maximum grain packing density for dry snow[9]. All of our shocked states are at higher densities and show even greater strain hardening than Abele and Gow found. This appears to be a rate dependent result.

4. CONCLUSIONS

Shock loading and release data are reported for snow with initial densities from 100 kg m^{-3} to 520 kg m^{-3} and initial temperatures ranging from -2 °C to -23 °C. The results for pressures up to 40 MPa indicate that snow is highly rate sensitive and compressible. The response of snow to shock loading is not dependent on initial snow temperature for the temperature range examined in this study. Quasi static tests and our shock measurements imply that snow compaction may occur by initial failure of snow grain bonds and grain rearrangement. Subsequent deformation occurs by plastic deformation of grains causing them to flow together.

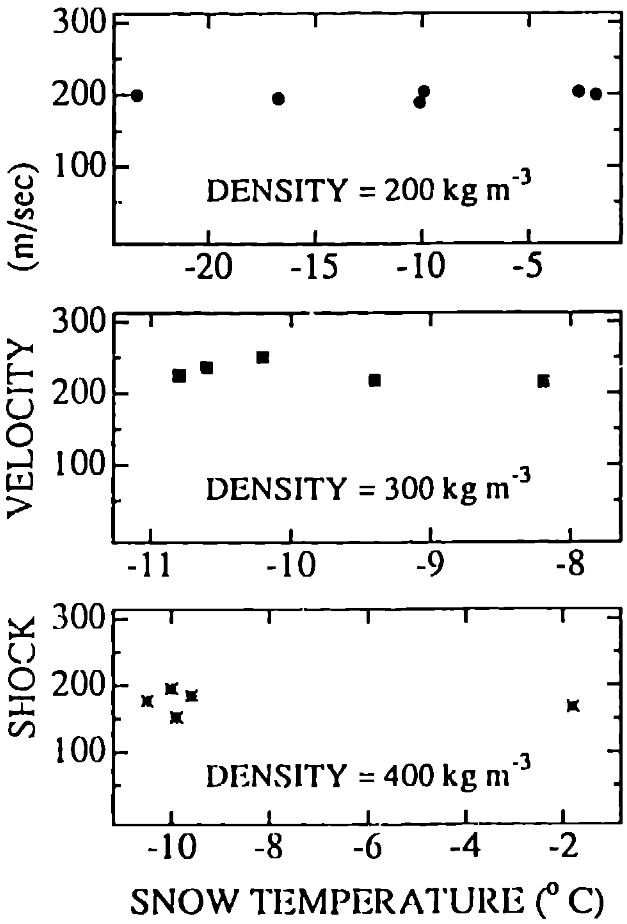

FIGURE 4
Shock velocity versus temperature for snow at constant density and particle velocity.

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